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PACKET RADIO--SYSTEMS CONSIDERATIONS

I. Introduction

The Packet Radio System is a broadcast extension of a link based packet communication system (such as the ARPA Computer Network) to accommodate various types of terminals without need of hardwire connections. The objective is to design an economic, reliable, and secure system for message and ultimately voice communication in which Packet Radio Terminals communicate with Packet Radio Terminals as well as information processors on the link based network. The Packet Radio System will operate in a broadcast mode using the ALOHA random access method.

There are three basic function components: the Packet Radio Terminal (T), the Packet Radio Repeater (R), and the Packet Radio Station (S). Packet Radio Terminals will be of various types including digital personal radios, voice personal terminals (operating in a packet mode), TTY like devices, unattended sensors, small computers, display printers and position location devices.

The digital personal radio as proposed by Roberts [1972] would be a small battery operated radio in which input would

be by "five capacity or stress sensitive buttons used by the fingers of one hand simultaneously to indicate one of 31 characters" and output would be displayed on a 2.8" x 1" plasma panel which can display either an 80 x 224 point graphic display or 256 (8 lines of 32) characters at about typewriter size. Portable packet voice communication terminals may be expected in the next decade which will operate at a bandwidth of 700-1000 bps by the use of various compression and prediction techniques. Such procedures already exist but do not generally operate in real time and are certainly not portable at this point in time. Many other I-O telemetry and control devices with a variety of traffic characteristics will also operate as terminals in the Packet Radio System.

The Packet Radio Station is the interface component between the broadcast system and the link based network. It will have broadcasting channels into the PRS and link channels into the link network. In addition, it will perform accounting, buffering, and directory and routing functions for the overall system.

The basic function of the Packet Radio Repeater is to extend the effective range of the terminals and the stations especially in remote areas of low traffic and thereby increase the average ratio of terminals to stations.

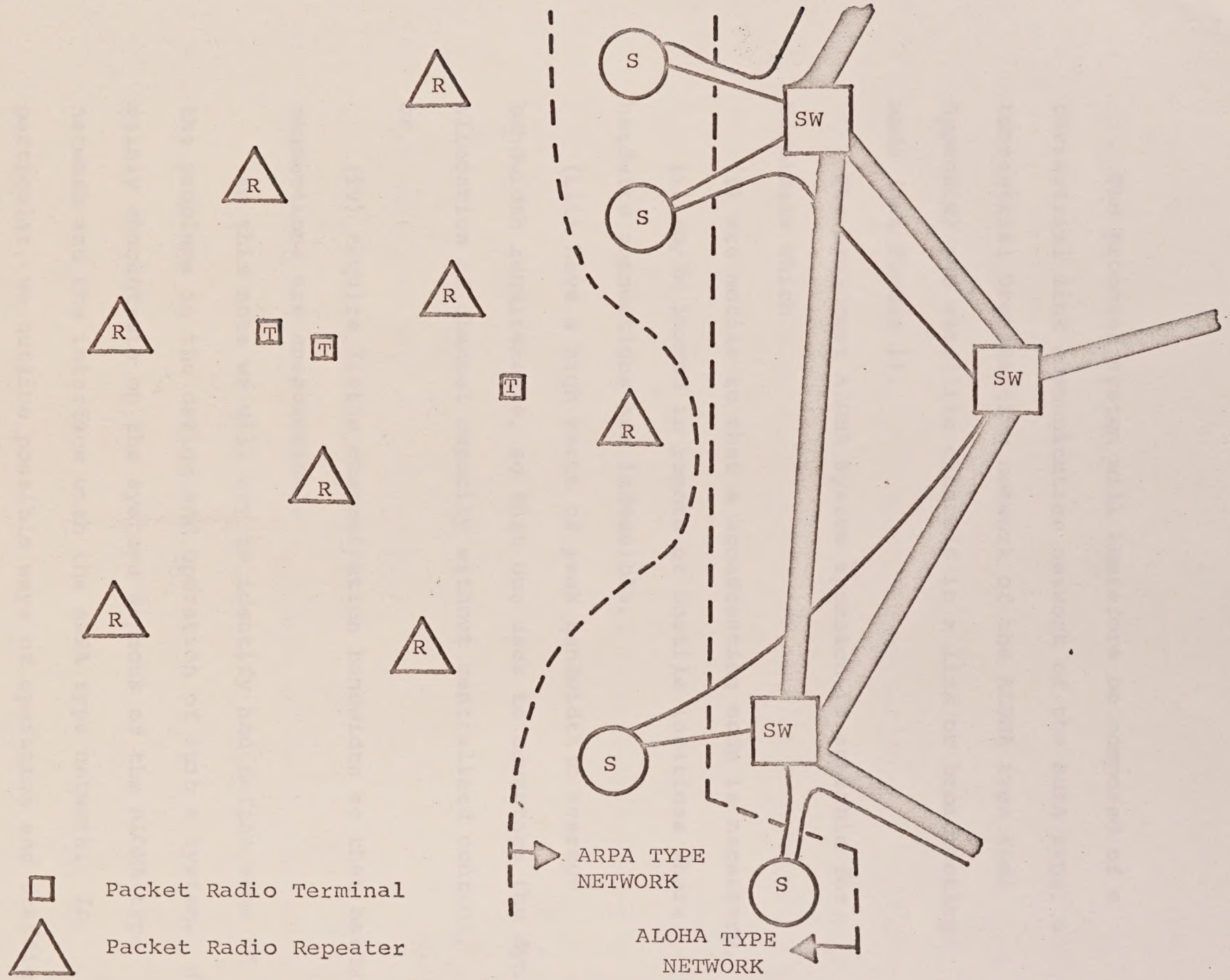
R
R
R
R
R
R
R
T
T
T
S
S
S
S
SW
SW
SW
ARPA TYPE
NETWORK
ALOHA TYPE
NETWORK
Packet Radio Terminal
Packet Radio Repeater
Packet Radio Station
Switch

FIGURE 1

The proposed system will therefore be composed of a terrestrial link communication network of the ARPA type, a terrestrial broadcasting network of the ALOHA type (see Appendix) and satellite channels in a link or broadcasting mode (see Figure 1).

The broadcast ALOHA System approach is suitable for terminals which :

(i) are mobile so that a broadcasting mode is necessary,

(ii) may be located in remote or hostile locations where hardwire connections are infeasible,

(iii) have a high ratio of peak bandwidth to average bandwidth requirements, so that one uses to advantage the dynamic allocation of channel capacity without centralized control, or

(iv) require little communication bandwidth so that hardwire connections are uneconomical.

In this note we will try to identify and define some of the problems in the design and operation of such a system. We mainly concentrate on the systems aspects of the ALOHA type network and the interface with the ARPA type network. In particular, we outline possible ways of operation and traffic control for packets transmitted by terminals until they reach the link network, identify some problems in the design of the network, and indicate possible system tradeoffs.

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II. First Order System Considerations

Stations will be allocated on the basis of traffic. Thus to first approximation we can think of partitioning the area to be covered (e.g. the United States) into regions of equal traffic and allocate one station for each region. In regions of low traffic density the station may well not be in line of sight of all the terminals in the region, hence repeaters are used to relay the traffic to the station. Thus repeaters correspond to a geographical partition of the area into sections small enough so that each terminal can communicate with a repeater and be relayed by it to a station. In areas of high traffic such as urban areas, repeaters will not be necessary; in fact the problem may be that a station can communicate with more terminals than it can handle.

As a gross estimate of the size of such a system, suppose the 3,536,855 square miles of land area in the United States are to be covered. Then if the average useful area that a repeater can cover is $\pi\, 10^2$ square miles, we would need approximately 11,258 repeaters.

In Table 1 a sample traffic distribution is given based on one due to Larry Roberts [Packet Radio Temporary Note 1; 1972]. We assume that the number of the various kinds of terminals is

TABLE 1--TEST TRAFFIC DISTRIBUTION[1]

(a) Traffic Type	(b) No./N[4] People	(c) Rates In Messages/ Second/ Device	(d) Rate Out Messages/ Second/ Device	(e) Message Size (without header bits)	(f) Fraction of Time Operating	(g) Device Peak Bit Rate In (c x e bits/sec)	(h) Device Peak Bit Rate Out (d x e bits/sec)	(i) Device Average Bit Rate In (c x e x f bits/sec)	(j) Device Average Bit Rate Out (d x e x f bits/sec) (exclusive of overhead)	(k) Total Average Bit Rate In b x c x e x f bits/sec (exclusive of overhead)	(l) Total Average Bit Rate b x d x e x f bits/sec	(m) Message Average Rate In c x f	(n) Message Average Rate Out d x f	(o) Acceptable Delay Secs.	(p) #of bits using 360 + 100 bit packets $\frac{\lceil e \rceil}{360}$ · 460 per device message (incl. overhead)	(q) Total Average Bit Rate In b x c x f x p (including overhead)	(r) Effective Total Traffic Out b x d x f x p (including overhead)
Compressed Voice	33	2.5	2.5	360	.03	900	900	27	27	891	891	.075	.075	.1	460	1138.5	1138.5
TTY& Personal Radios[2]	100	1.	.1	100	.04	100	10	4	.4	400	40	.04	.004	.5	460	1840.	184.
Unattended Sensors	160	0	.1	50	1.	0	5	0	5	0	800	0	.1	∞	460	0	7360.
Small Computer	1	10	1	1000	.05	10000	1000	500	50	500	50	.5	.05	.5	1380	690.	69.
Display Printers[3]	1.6	10	0	1000	.05	10000	0	500	0	800	0	.5	0	.5	1380	1104.	0.
Position Location[6]	50	0	.01	0	1.	0	0	0	0	0	0	0	.01	.5	460	0	230.
TOTAL	345.6									2591.	1781.	1.115	.239			4772.5	8981.5

2591. + 1781. = 4372

4772.5 + 8981.5 = 13754.0

Notes:
1. Traffic based on estimates by Larry Roberts 12/72
2. Personal Radios added in with TTY
3. Display Printer packet rate out given as 1 by Roberts here modified to 0.
4. Number of devices assumed to be per N people.
5. $\lceil n \rceil$ is the smallest integer greater than or equal to n.
6. Position Location information assumed to be in packet header
7. Message size assumed the same for incoming and outgoing messages.

proportional to population. Thus N people would generate 2591 bps into the terminals and 1781 bps out. This makes no allowances for a packet header, ALOHA interference, artificial traffic due to repeaters, acknowledgments, or other overhead.

We assume a one frequency system with 100 Kbps channel capacity, used in a slotted ALOHA mode. Due to conflicts from interference between packets using a slotted random access ALOHA channel the maximum bandwidth is reduced to 1/e of the nominal value or 36788 bps.

On the other hand from Table 1 we see that N people will generate 13754 bps including overhead if we assume a packet size of 360 bits of information plus 100 bits of header. Of this 13754 bps only 4372 is useful information; the rest is overhead--packet headers and wasted space due to partly filled packets. Thus the channel has an effective peak utilization of $\frac{1}{e}\ (\frac{4372}{137534}) = .11694$ yielding for our 100 Kbps channel a maximum rate of useful information of (.11694)(100,000) = 11694 bps.

The appropriate choice of N to scale the traffic is rather arbitrary. Table 2 contains the number of stations, the number of people per 100 Kbps channel, the number of stations outside the large metropolitan areas, and the population density at which the population associated with a station covers the same area as a repeater all as a function of N assuming a 100 Kbps

channel. In Table 3, the ratio of repeaters to stations is related directly to traffic density in bits per second per square mile.

For large N the stations will replace repeaters in providing area coverage to some extent; the extent to which this occurs depends on the distribution of population density. The average population density in the U.S. is 57.6 people/square mile and the density in the states ranges from 0.5 people/square mile in Alaska to 953.1 people/square mile in New Jersey. The density in Manhattan in New York City is 67,808 people/square mile.

On the other hand, at high traffic levels $N < 10{,}000$ or traffic density > 100 bps/square mile, repeaters play a much smaller role since the system is now traffic limited. In extreme cases repeaters may not even be necessary; however, there will be a very large number of stations and it will most likely be necessary to do some multiplexing or concentration before entering anything like the ARPANET.

If one considers the 148 Standard Metropolitan Statistical Areas (SMSA) with more than 200,000 population, they have a total of 127,417,000 out of the 203,166,000 people in the United States in 301,661 square miles out of the 3,536,855 square miles

People/ mi.²

TABLE 2

N	Stations	People/ 100 Kbps Channel	Station Outside SMSA's	Repeaters/ Stations Outside SMSA's	Critical Population Density
100	759570	267	283200	.04	.85
1000	75957	2675	28320	.37	8.51
10000	7596	26747	2832	3.73	85.14
100000	760	267475	283	37.31	851.40
1000000	76	2674748	28	373.16	8513.98

TABLE 3

Traffic Density bps/sq mi	Sq.miles per channel (100 Kbps or 11693 bps effective)	No. of Repeaters (with 10 mile effective radius) required per station)
1	11694	37
10	1169.4	4
100	116.9	0
1000	11.7	0
10000	1.2	0

of land area in the United States. Thus, the 148 SMSAs would correspond to enough area for 960 outof the 11258 repeaters , many of which could be replaced by the stations for area coverage. In the remaining part of the U.S., 10,568 repeaters would be required.

We can already draw several preliminary conclusions from this crude analysis. For low traffic levels, $N > 100,000$ or traffic density < 10 bps/sq mi. the number of stations $<<$ number of repeaters $<<$ number of terminals; hence, the assignment of functions to components should be such that the terminal is as simple and cheap as possible, the repeater only slightly more sophisticated and as many functions as possible should be delegated to the relatively few stations and the link packet communication network connected to them.

III. Some Factors to be Considered in a Second Order Systems Analysis

Many more factors affect the location of repeaters and stations than the simple ones singled out in the last section. The naive calculations used to calculate terminal to station fanouts and repeater to station fanouts also neglect important considerations. Moreover, the device of considering repeaters simply as area covers and the station as traffic covers also neglected important interactions between the two types of devices. In this section we try to point out some of these complicating aspects.

Factors affecting the location of repeaters and stations besides range and traffic which were previously considered are:

(i) Logistics: certain locations for repeaters may be much preferrable to others in that they may be more accessible or there may be available power so that batteries need not be used, e.g. on telephone poles or near power lines. Stations should preferably be placed near existing facilities of the associated ARPA like network.

(ii) Reliability and redundancy: for a multitude of reasons redundant repeaters and stations will be required. Repeaters in remote areas will (very possibly) be operating on batteries which will fail and it would be nice to have

sufficient redundancy so they will not need to be replaced immediately. Stations and repeaters will have intermittent and terminal failures for which backup is required. Extra repeaters are desirable when line of sight to the primary repeater is locally blocked. There will be random variations in repeater and station manufacture and placement which will cause inadequate or misdirected performance. This will have to be provided for by a safety margin of redundant coverage in the design.

(iii) Delays and throughput reductions due to collision and retransmission of packets: when a single channel is being operated in an ALOHA radom access mode, no more than 1/2e of the bandwidth can be used in the unslotted case and no more than 1/e in the slotted because of retransmissions resulting from packet conflicts. This was taken account of in the previous section (note: Spread bandwidth coding techniques may improve this figure); however, there is extra traffic generated due to the repeaters and conflicts due to adjacent stations. The delays caused by retransmissions completely dominate the delays due to (i) and (ii) above. Some sources of retransmissions are:

(a) In order for the Packet Radio System to be reliable, it will be necessary, in general, that several repeaters or

stations be within range of each terminal. If the repeaters retransmit everything they hear, one message can generate an exponentially growing number of relayed messages. In order to keep one message from saturating the whole network, some means of traffic control is required. The discipline chosen and its efficiency will probably be the single most important system factor affecting system performance. Two types of undesirable routing through the repeaters can occur. A message can circulate endlessly among the same group of repeaters if not controlled but even if this does not occur a message can be propagated in a geometrically increasing number of new repeaters.

(b) Again for system reliability more than one station must be able to transmit via repeaters to each terminal. This means there will necessarily be conflicts between adjacent stations reducing the bandwidths from their nominal value and also introducing coordination and routing problems in the process.

(c) Because in general there will be many routes between any given terminal and any given station many more conflicts will result than would be the case if the terminals communicated directly with a station.

Extraneous traffic can also be generated in the ARPA like network if several copies of the same message enter the network from different stations. Either this can be sorted out on entry

to the stations or at the destination. In the latter case the traffic is artificially increased and in the former much more computation has to be performed by the stations to maintain coordination.

IV. Routing and Control of Traffic Flow in ALOHA Type Network

The transmission reception operations between a single terminal and a single station are described in [Roberts; 1972]. In this section, however, we assume that there are many possible paths for a packet originating at a terminal until it is received by the station. That is, a packet transmitted from a terminal can be received by several repeaters and that there may be several stages of repeaters before the packet is received by a station.

There are problems which can arise in controlling traffic flow in a large scale broadcasting network which one does not encounter in link communication networks. Some of these are:

1) A packet transmitted can be received by many repeaters or stations or not be received by any.

2) Many copies of the same packet can circulate in the broadcasting network.

3) Many copies of the same packet can enter the ARPA type network at different stations.

4) Different parts of one message can enter the ARPA type network at different stations.

Note that the proposed ALOHA type network is different from the ALOHA System at the University of Hawaii [Abramson;1970]

in that the latter is a centralized system and also does not include repeaters. As a result, one does not encounter any of the problems of traffic control indicated above.

Some indication of the difficulty of the problem when no controls are imposed can be learned from the ideal case analyzed in Packet Radio Temporary Note 6. In this ideal model the repeaters are located at corner points of a square grid at distances of one unit(time), a packet transmitted by a repeater is correctly received (only) by its four nearest neighbors, a packet received by a repeater is immediately repeated. Suppose now that a single packet originates at the origin and that the transmission plus the propagation time is one unit of time, then after n units of time we have: (i) the number of repeaters which receive the packet for the first time, B(n), is:

$$B(n) = 4n, \quad n \geq 1; \quad B(o) = 1$$

(ii) the number of repeaters that the packet went through, A(n), is:

$$A(n) = \sum_{j=0}^{n} B(j) = 2n^2 + 2n + 1, \quad n \geq 0$$

(iii) if we assume that a repeater can receive and relay a large number of packets at the same time, then the number of copies of the same packet received by a repeater at coordinates

(d,j) after d+2K units of time is:

$$N_j^d\ (d+2K) = \binom{d+2K}{k+j}\binom{d+2K}{k} \text{ for } \underline{\text{large K}} \rightarrow 2^{4K}$$

where d is the number units of time that the packet needs to arrive from the origin to the repeater, and j is the horizontal number of units.

Thus unless some steps are taken this explosive proliferation of redundant packets will severely limit the capacity of the system.

One can recognize two somewhat distinct routing and control problems:

(1) To assure that a packet originating from a terminal arrives to a station; preferably using the shortest path.

(2) To suppress copies of the same packet from being indefinitely repeated in the network either by being propagated in endless cycles of repeaters or by being propagated for a very long distance.

The following methods can be used for the suppression of indefinite packet propagation:

(A) A maximum handover number as in the hot-potato routing [Boehm & Baran; 1964], [Smith; 1964]. Each time a packet is retransmitted the handover number in the packet is incremented by one. If the handover number exceeds

an assigned maximum, the packet is dropped. If the maximum handover number is set to be large, extensive artificial traffic may be generated in populated areas; on the other hand, if it is set to be small, then packets from remote areas may never arrive at stations. This problem can be resolved as follows: We assume that every repeater knows its approximate distance to stations from observing response packets. The first repeater which receives the packet from a terminal sets the maximum handover number based on its distance from the station. The number is then decremented, rather than incremented, at every other repeater . The packet is dropped when the number reduces to zero. When a station transmits a packet it will set the maximum handover number by "knowing" the approximate radius in "repeaters" in its region.

(B) Repeaters can save the header of packets (or possibly the entire packet) for a specified period of time to be compared with headers of packets (or with packets) received. If the same packet is received by a repeater the second time, it is not retransmitted.

In what follows we propose three routing techniques which can be used for broadcasting networks. In all methods it is assumed that a repeater knows whether a packet is addressed to

a terminal or to a station. This is indicated either by the transmission frequency or by means of a bit in the header of the packet when the same frequency is used in both directions.

Method 1: Regionalization

The principle of this method is that every packet will contain several bits for a "regional address". This address is associated with one or more stations in a region, and possibly many repeaters.

Transmission from terminal to station: When a packet originates from a terminal it has a blank "regional address". If the packet is received by a repeater (with a correct check sum) and it has a blank regional address or the same regional address as the receiving repeater, it is retransmitted with the regional address. If the packet received has a regional address which is different from that of the repeater, it is dropped. A station which receives the packet will transmit a display acknowledgment to the terminal. When a response packet is received by a repeater it is repeated, again with the regional address. The terminal will time-out and retransmit the packet if an acknowledgment has not been received with an indication that it is the same packet [Roberts; 1972].

Transmission from station to terminal is the same as above.

When transmitting from a terminal to a station, it is possible that parts of the message will be received by several' stations in the same region, or in different regions when the terminal is located at a boundary. To overcome this, it is possible to have several bits in the packet heater for indicating the station ID. After the terminal has received an acknowledgment for the first packet, it will transmit the other packets of the same message with the ID of the station. Other stations which received and acknowledged the first packet will save it for a "specified period of time" and drop it if more packets of the same message are not received.

Method 2: One Level Labeling

By this method one obtains shortest path routing in one direction, from the terminal to the station. In this method and in Method 3, it is assumed that packets are routed using "hop-by-hop" transmission, i.e. a repeater stores the packet and keeps retransmitting it until acknowledged by the next repeater stage. It is also assumed that if device i can receive from device j, then device j can receive from device i.

For routing purposes every repeater i is characterized by the triple $(R_i, L_i, \overline{R}_i)$ where R_i is its identity number, L_i its label which indicates the number of hops in the shortest

path to its nearest station, and $\overline{R}_i$ is the identity of the next repeater on the shortest path to the nearest station. For one level lebeling R_i is fixed whereas L_i and $\overline{R}_i$ are modified to reflect changing conditions in the network.

The ALOHA type network is periodically relabeled by labeling packets from the stations, to adapt to a new state of the network. R_i relabels itself upon receiving a labeling number L_k from another repeater or station by:

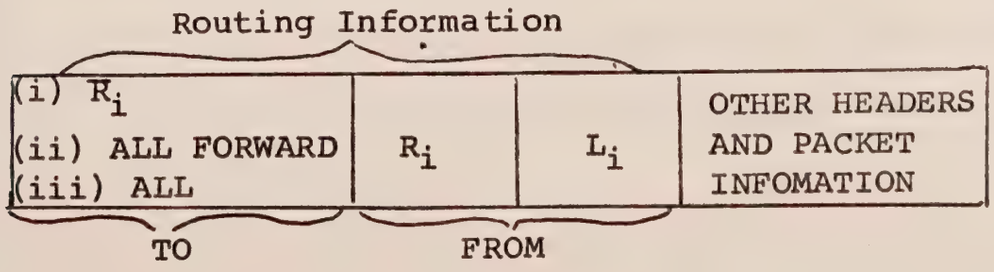
$$L_i \text{ (new)} = \min[L_i \text{(old)}, L_k+1]$$

If L_i(new) = $L_k + 1$ then $\overline{R}_i$ is set to R_k.

When the network is labeled, then every repeater knows the next repeater on the nearest path to the station.

Transmission from Terminal to Station: The first packet (or a signaling packet) transmitted from a terminal is addressed to all repeaters. A repeater which correctly receives this packet acknowledges it with its R_i and thus stops the retransmission of that packet. All future packets of the same message will be addressed to R_i and retransmitted by the terminal until acknowledged by R_i.

The packet transmitted from repeater to repeater up to the station includes the following routing information:



The packet is first transmitted to $\overline{R}_i$ for a specified number of times. R_i waits for a certain deterministic plus random time before each retransmission. If the packet is not acknowledged by R_i after the specified number of times then it is transmitted to ALL FORWARD (AF), again, for some (possibly different) specified number of times. AF means that the packet is addressed to all receivers with a smaller label. Thus when a repeater receives a packet with AF it has to check its label against L_i. If the packet had not advanced with AF, then the next (last) step would be to transmit to ALL. ALL addresses the packet to all repeaters that can "receive" it. In particular it means that the packet can travel backwards and try a new path. When ALL is used it is possible, although with very low probability, that a packet will be transmitted in a cycle. Several procedures can be used for preventing the latter.

Transmission from Station to Terminal: The labeling of repeaters does not include sufficient information for directing transmission from the station to the terminal on the shortest path. This is particularly true when a packet is originally delivered to its destination.

To reduce the repetition of packets in this direction, however, one can use an address ALL BACKWARD (AB) by all repeaters.

When AB is used by repeater R_i, the packet is addressed to all repeaters R_k for which $L_k > L_i$. This assures the suppression of packet repetition after it propagates once through the network. Another possibility is to regionalize the network.

A simplified version of Method 2 is without the labeling. The first packet originating from a terminal establishes a unique path through which other packets of the same message will be transmitted. Packets can be addressed either to $\overline{R}_i$ or to ALL. The first packet from a terminal will be addressed to ALL. The repeater which received it will acknowledge it with its R_i. Other packets of the same message from the terminal will be addressed to R_i. R_i will respond only to packets addressed to it or to ALL; all other packets will be dropped. Repeaters are not mobile and can "learn" the location of the nearest station or repeater. Thus R_i can start transmitting to a specific $\overline{R}_i$, and use ALL as the second option. A station will also respond only to packets addressed to it or to ALL. When a positive acknowledgment is received from more than one repeater or station then all, but the first, can be ignored. Note that this method does not guarantee the shortest path; however, it selects one which seems not congested at this point in time.

Method 3: Hierarchical Labeling

This method enables shortest path routing from terminal to station as well as from station to terminal. The packet header will contain sufficient information for determining the next repeater on the shortest path in each direction. The principle is similar to that expressed in [R. L. Graham and H. O. Pollak; 1971].

Consider the case in which the ALOHA type network is labeled as in Method 2. Then the network has an inherent hierarchical (tree) structure where every repeater "homes" on the repeater or station from which it was labeled, as in the following figure:

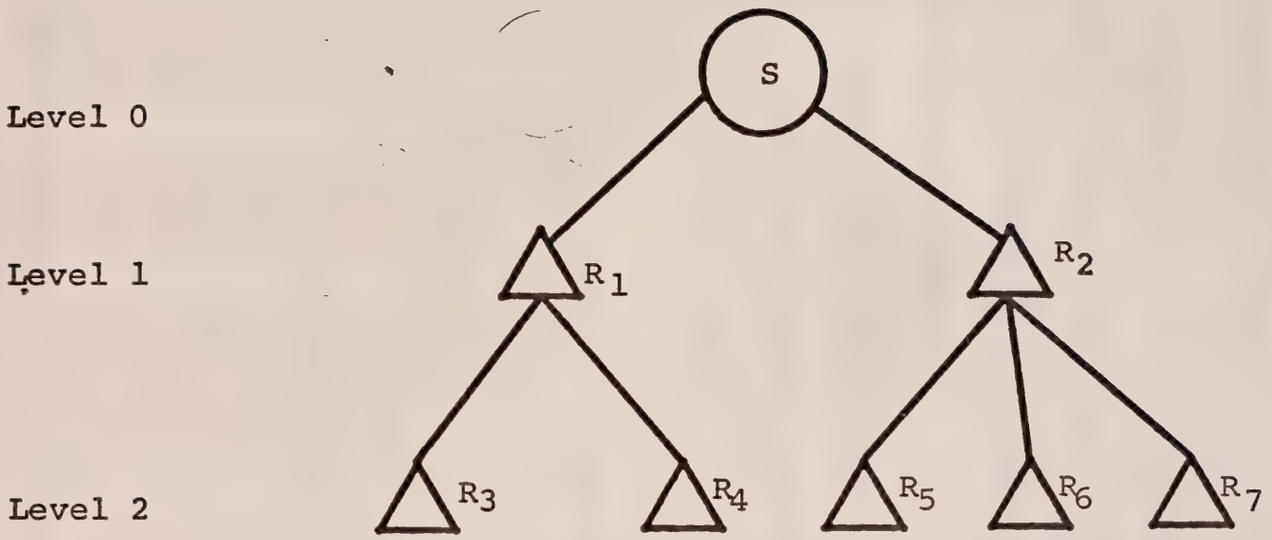


FIGURE 2

Suppose now that the identity number of each repeater is composed of h subfields, where h is the maximum number of hierarchy levels; and that repeaters which "home" on the same higher level (in the hierarchy) repeater are sequentially ordered. When this is done then shortest path routing can be obtained in both directions.

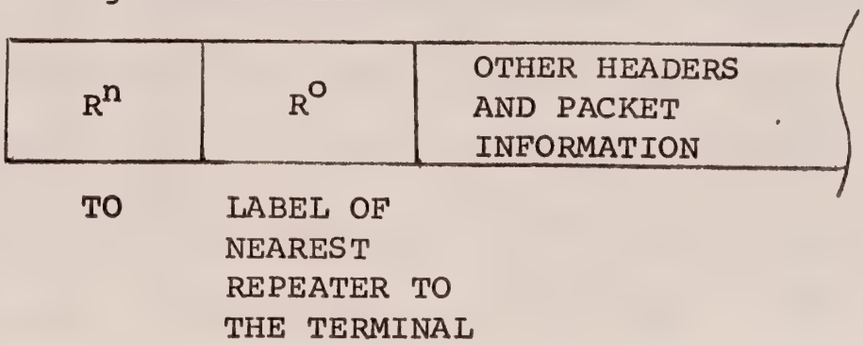
Every subfield has three possible entries, blank, a serial number, or ALL. The label of a repeater R_i in hierarchy level j will be composed of h subfields in which the last (h-j) subfields are blank.

As an example for the network in Figure 2; if we take 3 bits per subfield then the identity numbers of the station and the repeaters can be as following:

	Subfield 1	Subfield 2	Subfield 3
S	0 0 1	0 0 0	0 0 0
R_1	0 0 1	0 0 1	0 0 0
R_2	0 0 1	0 1 0	0 0 0
R_3	0 0 1	0 0 1	0 0 1
R_4	0 0 1	0 0 1	0 1 0
R_5	0 0 1	0 1 0	0 0 1
R_6	0 0 1	0 1 0	0 1 0
R_7	0 0 1	0 1 0	0 1 1

In this example a subfield in which all bits are "0" is considered "blank". Note that all entries in Subfield 1 are the same since all repeaters home (eventually) on the same station.

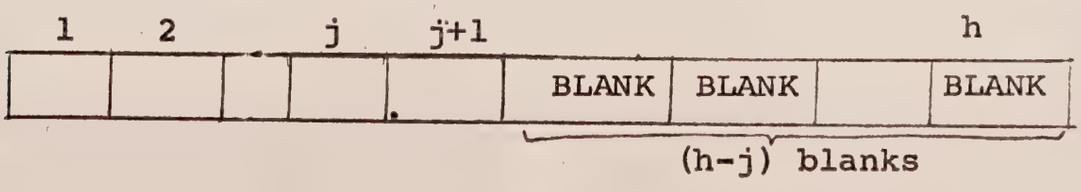
The packet header, in both directions, will include the following routing information.



R^o is the repeater or station which first acknowledged the first packet of the message and R^n is the identity number, in this case also the address, towards which the packet is currently addressed.

Transmission from Terminal to Station: The first packet transmitted from a terminal is addressed to ALL. The repeater which acknowledges the packet also sends its identity number. This number is R^o. All other packets of the same message will be addressed by the terminal to R^o. R^o will be carried all the way to the station.

Suppose that R_i of hierarchy level j contains the packet. The identity number of R_i is as shown below:



R_i times out and retransmits the packet for a specified number of times to the repeater on which it homes. The address of this next repeater is the same as that of R_i, except that the (j+1)st subfield is set to be blank. If the packet is not acknowledged then it is addressed to AF, again for some specified number of times. There may be several stages of AF depending on how many of the higher level subfields are set to "ALL". The next possibility is to address the packet to ALL. The address ALL is again similar to that of R_i where in the latter one replaces by "ALL" the subfields of j, j+1, and (j+2). The packet is then addressed to all repeaters whose hierarchy level is that of R_i, one level above or one level below. Again, there may be several levels of ALL depending on how many subfields above and below that of R_i are replaced by "ALL". Note that R_i does not need to know where the packet came from. Repeaters will respond only to packets addressed to their specific number, or if their specific subfield is ALL.

Transmission from Station to Terminal: R^o contains the information for the shortest path transmission to the terminal. The station transmits the packet to the repeater in which the first two subfields are specific (these of R^o) and all other blank. A repeater of

hierarchy level j addresses the packet next, to the address in which the first (j+2) sublabels are from R^o and the remaining are blank. All other aspects of transmission, such as specific address, AB, or ALL, are similar to these in the reverse direction.

Note that the packet may depart from the shortest path when addressed to AB . When this happens then in the next stage the packet tries to get back onto the shortest path by bypassing only the repeater that was busy or down.

To conclude, when the packet is routed from the terminal to the station and departs from the shortest path, it uses the shortest path from its new location; on the other hand, it tries to get back onto the original shortest path when routed to the terminal.

Remarks

(1) In Method 3, when the packet arrives to a station it contains the address of the "nearest" station to the terminal (the first subfield of R^o). It may be feasible to transmit this packet to its nearest station via link channels between the stations. If this is not done, then one may consider routing from terminal to station the same as from station to terminal; i.e. to try and get back onto the original shortest path.

(2) Many problems that may be encountered in routing and control of traffic flow have not been considered. In particular algorithms for labeling and relabeling of repeaters.

(3) The "echo" type of acknowledgment where a terminal or repeater knows whether its transmission to a repeater is successful by listening to the latter repeaters transmit is not as effective as in a satellite channel [See ASS Notes]. Because of FM capture the first repeater may be blocked from hearing the "echo" while the packet is successfully relayed. If a two frequency system is used, one for packets traveling towards the station and another for return, then the terminal will be listening to the return frequency while the echo is on the other frequency.

(4) If the ID to which a message is addressed cannot be found in its original location, then an information bank should be available where the new location can be found. The change of IDs' location can be recorded in a central or area-coded directly computer as proposed in [Roberts; 1972], or at the station of the original location as suggested in [Baran; 1964].

V. Hardware Functions

In this section we discuss only the functional capabilities of the devices which are necessary for communicating in the ALOHA type network. That is, it relates only to the hardware which interfaces with the broadcasting network.

Terminals: There are two categories of terminals; (i) those which usually await a response to a message that they transmit (e.g. manually held radio terminals, small computers), and (ii) those which do not need any response or acknowledgment (e.g. unattended sensors, position indicators). Some terminals in the former category will usually send and/or receive several packets in one message. Another characteristic of this category is that the terminal is usually operated by a person.

The necessary capabilities of terminals in category (i) are:

(1) To identify whether the packet is addressed to their ID.

(2) To check whether the packet has a correct sumcheck.

(3) Some of these terminals will have character generation logic.

(4) Some of these terminals will have a random number generator when using random waiting time for retransmission; others may be assigned a random number for this purpose.

(5) Capabilities related to packet routing such as: terminating retransmission when acknowledged, recording and using a specific ID of a repeater and/or station to be used for other packets of the same message, counting the number of retransmissions.

(6) Capabilities related to the response to various, previously determined, types of error (see also [Roberts; 1972]).

The capabilities of terminals of category (ii) are:

(1) Since these terminals are not operated by man they may have some functional capabilities by which a centralized control or a station will be able to identify whether the terminal is operative or dead. This may depend on the frequency at which the terminal transmits and the type of information.

(2) Those terminals which transmit "important" information or in general when it is important to receive all packets transmitted, should have the capabilities related to retransmission of the packet until acknowledged (see (4) and (5) above).

Repeaters: The functional capabilities that repeaters should have are:

(1) To check whether a packet has a correct sumcheck and retransmit it.

(2) Capabilities by which a station can determine whether a particular repeater (or any repeater in a particular area) is operative or dead.

(3) When more "sophisticated" routing is used then repeaters should have the capabilities (1), (4), and (5) of terminals from category (i).

(4) Again, depending on the routing the repeaters may have additional capabilities related to derermining the next repeater on the shortest path, changing addresses to AF, ALL AB; capabilities related to labeling and relabeling.

Stations: The station will have a broadcasting channel for communication with terminals and link channels connecting it to a Digital Switching Machine (SW) in the high speed ARPA type network. The switching machine may be similar in function to an IMP or a TIP. Every station will home on one SW with possibly a second for an alternative when the prime channel is down. It may be feasible that alternative channels will be used simultaneously under certain overload conditions. The station should have the following functional capabilities

(1) Cryptographic apparatus suitable for handling sensitive and private messages.

(2) A directlry of terminals (and possibly repeaters) in its region.

(3) Operations necessary to convert short packets from ALOHA type network into long packets used in the ARPA type network.

(4) Storage buffers for packets received from terminals and packets to be transmitted to terminals.

(5) Storage for character position information for active terminals.

(6) Character generation logic.

(7) If station will be used to "connect" terminals in its region without going through the switched network, then it should have accounting capabilities.

(8) Capabilities related to routing of packets such as items (3) and (4) above.

Some of the above functions are optional and can be performed in the switched network. For example (2), (3), and (7).

VI. Transmission Power and Reception Sensitivity of Devices

Assuming that most of the terminals will operate in an urban area then the transmission power of this device should be low. A low transmission power will be sufficient to reach stations and yet not saturate them. When a terminal operates in a rural area, we would like it to have a long range. Thus, if a terminal has only one transmission power it implies that the receiving sensitivity of repeaters should be high.

Reliability considerations may require that every terminal should be able to reach at least two repeaters or stations. This also implies that every repeaters with the same transmission power as that of a terminal will in general be able to reach at least two other repeaters or stations in the same location pattern. Thus, the transmission power of repeaters can be kept low, in the order of that of a terminal. Another reason for having a low repeater transmission power is to enable the capture of a packet transmitted from a terminal. To go on with this argument, if we require that every terminal should be able to receive a packet from at least two repeaters in every location, it requires that the terminal's reception sensitivity should be high.

In the discussion above it was assumed that every terminal has the same constant transmission power. One could resolve the conflicting power requirements between urban and rural use of terminals by having the transmission power adapt to the local requirements. This is usually what people do when they speak and cannot be heard. Specifically, every device keeps retransmitting the packet with increased power until acknowledged, up to some maximum specified number of times, thus increasing its probability of being captured each time. Of course, if the transmission is not successful because of collision with another packet then an increase in the transmission power of both transmitters will not resolve the problem. Many aspects of this approach need study, for example, if the first packet was acknowledged when transmitted with power P; what power should be used for transmitting the second packet. The method also has the interesting feature: that given some number of transmitters equally distant (approximately) from the receiver, one tends to get first come first served service discipline.

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APPENDIX

ALOHA System and Capture Ratio

The above notions used throughout this note are now explained. By ALOHA transmission we mean the use of a channel in which the channel is randomly accessed by more than one user. The users transmit equal size packets using the same speed, equal to the channel speed. Two modes of operation are indicated; a non-slotted (asynchronous) mode in which users can access the channel at any time and a slotted (synchronous) mode in which users can access the system only at the beginning of a slot. The synchronization referred to is that between users. The theoretical results assume a no-capture system. That is, if two or more packets overlap, none of them is correctly received, and each has to be retransmitted.

Assume that there is an infinite number of users and that the point process of packet origination and also the point process of packet originations plus retransmissions are both Poisson with mean σ and γ, respectively; also that the constant transmission time of a packet is T. If a packet is starting at some random time, then the probability that it is correctly received (no overlapping, collision, conflict) in the non-slotted case is $e^{-2\gamma T}$. The reception rate, equal to the

origination rate (assuming that packets that collide are retransmitted until correctly received) is $\sigma = \gamma e^{-2\gamma T}$. The effective channel utilization is therefore

$$\sigma_T = \gamma T \, e^{-2\gamma T}$$

Evaluating the maximum utilization one obtains $\text{Max}(\sigma T) = 1/2e$. For the slotted case the probability of collision is $e^{-\gamma T}$ rather than $e^{-2\gamma T}$ which leads to $1/e$ as the maximum utilization. γT is referred to as channel use, it equals $1/2$ and 1 at maximum effective utilization for the non-slotted and slotted case, respectively [Abramson; 1970].

For the finite number of users case [ASS Note 26], let us suppose that the slot width is normalized to be 1, that the channel is being shared by m independent identical users, and that g is the probability of a new packet from one user arriving for a given slot. If G is the probability of a new packet or a retransmission we have

$$g = G(1-G)^{m-1} \qquad (*)$$

G can be controlled by varying the random time out between retransmissions. The useful traffic is mg packets per slot on the average. Its maximum value $(mg)^*$ is obtained by maximizing (*). Thus

$$0 = \frac{dmg}{dG} \text{ implies } G = \frac{1}{m} \text{ and } (mg)^* = (1 - \frac{1}{m})^{m-1}.$$

Since the slot period was normalized to 1 $(mg)^*$ is also the utilization. For $m \rightarrow \infty$ $(mg)^* \rightarrow \frac{1}{e}$. For m=2, 3, 4, 5 $(mg)^*$ is .5, .4444, .4218, and .4096 respectively. Thus, for just two users sharing a slotted channel the utilization is already 1/2 and with 5 users is within 10% of the value for an infinite number of users.

FM Capture Ratio: When two signals with power P_1 and P_2 $(P_1 > P_2)$ arrive simultaneously to an FM receiver, the receiver can correctly receive the stronger signal providing $P_1 >> P_2$. An FM receiver is characterized by the ratio of power in dB between the strongest signal and the next to strongest, necessary for correctly receiving the former.

$$CR = 10 \log (P_1/P_2)$$

When the transmission power of transmitters is assumed constant (or insignificant variations) then the CR implies a certain distance ratio from transmitters to receiver.

A no capture receiver is one for which $CR \rightarrow \infty$, and a perfect capture receiver, one for which $CR \rightarrow 0$.